Bayesian Hierarchical Models to Augment the Mediterranean Forecast System

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LONG-TERM GOALS

The long term goal, spanning both phases of the research program, is to demonstrate Bayesian Hierarchical Model (BHM) utility in several aspects of operational ocean forecasting. The specific goal in Phase II (beginning June 2007) is to complete a proof-of-concept demonstration of BHM methods in SuperEnsemble (SE) ocean forecasts. Multi-model and multi-parameter demonstrations are being developed in MFS-SuperEnsemble-BHM.

Goals from Phase I (beginning June 2005) include: a) development of an operational ensemble ocean initialization and forecast methodology based on surface wind realizations from MFS-Wind-BHM; and b) implementing a time-dependent background error covariance matrix in the Mediterranean Forecast System (MFS) three-dimensional variational (3DVAR) assimilation system via MFS-Error-BHM.

OBJECTIVES

Research objectives for the completion of Phase I in the past year included:

1) developing metrics to distinguish versions of the MFS-Wind-BHM that differed in the level of explicit physics in the prior distribution models;

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14. ABSTRACT **The long term goal, spanning both phases of the research program, is to demonstrate Bayesian Hierarchical Model (BHM) utility in several aspects of operational ocean forecasting. The specific goal in Phase II (beginning June 2007) is to complete a proof-of-concept demonstration of BHM methods in SuperEnsemble (SE) ocean forecasts. Multi-model and multi-parameter demonstrations are being developed in MFS-SuperEnsemble-BHM.**					
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2) documenting the versions and distinctions of MFS-Wind-BHM, with a goal to identify the model version to be implemented in MFS operations;
3) developing the MFS-Error-BHM for testing in the MFS research ocean model; and
4) drafting manuscripts to document MFS-Wind-BHM and MFS-Error-BHM developments.

Research objectives in the organization of Phase II include:

1) run-matrix design for multi-parameter super-ensemble experiments in MFS; and
2) Mediterranean forecast model development plans for MedROMS, a second basin-scale ocean forecast system to be used in multi-model MFS-SuperEnsemble-BHM experiments.

APPROACH

Phase I:

Model verification studies and model version selection for MFS-Wind-BHM will be described in Milliff et al. (2008). Initial impacts in ensemble ocean initial condition derivation, and ensemble ocean forecasts will be described by Bonazzi et al. (2008). Bonazzi (2008) organizes the process model options for MFS-Wind-BHM into two atmospheric model forms: A1) involving explicit terms for the leading-order pressure gradient terms (geostrophic and ageostrophic); and A2) that also makes explicit next-order terms from the Rayleigh Friction Equations (Stevens et al., 2002), including a time-dependent term and a mixed time-space second derivative term. Bonazzi (2008) also explores three versions of an error model to represent process model misfits and sub-grid scale processes. We are excluding our further development and testing of MFS-Wind-BHM to the third error model variant (E3) involving a nested wavelet expansion (e.g. see Wikle et al., 2001). We continue to perform sensitivity tests for MFS-Wind-BHM versions A1E3 and A2E3 in experiments involving many tens of thousands of iterations of the respective Gibbs Samplers.

The impacts of the first implementations of MFS-Error-BHM are being tested in reforecast experiments at INGV for MFS sub-region 3 (Gulf of Lyons). Refinements in the data stage inputs and data stage distribution calculations are also planned for MFS-Error-BHM. Time-dependent anomaly inputs will be taken from a more recent MFS reanalysis, and anomaly data will be provided for all grid locations within the MFS sub-region (instead of only at ARGO locations as before).

Phase II:

The BHM constructs for SE climate forecasts put forward in Berliner and Kim (2008) form the theoretical basis for the ocean SE forecast experiments. Berliner and Kim (2008) develop BHM components for combining forecasts (and, optionally, relevant observations) to generate a posterior distribution for the forecast as well as distributions for model biases and the representativeness of the forecast process of interest in any model. The posterior distribution is given by:

$$[\mathbf{X}, \beta, \mathbf{b}_m, \mu_m, \sigma^2_{Y_m}, \sigma^2_{\beta}, \sigma^2_{b_m} | \mathbf{Y}_m]$$

where X is the Mediterranean Sea process of interest, and Y_m are deterministic model summaries of that process from m different models. The key concept in the SE BHM is the formation of a single data stage distribution hierarchy given by:

$$\mathbf{Y}_m|\beta, \mathbf{b}_m \sim Gau((\beta + b_m)\mathbf{1}_{n_m}, \sigma^2_{Y_m}\mathbf{I}_{n_m})$$

$$\beta|X \sim Gau(X, \sigma^2_\beta)$$

$$b_m|X \sim Gau(\mu_m, \sigma^2_{b_m}\mathbf{I}_{n_m})$$

Here, β is the representativeness of the process X in the ocean forecast models, b_m is the bias term for each model, and the σ^2 are the variances.

The first objectives in Phase II are to identify an appropriate X, and construct useful Y_m, β and b_m. The time-dependent formation of Levantine Intermediate Water (LIW) in the Rhodes Gyre region is an oceanographic process of interest that we seek to estimate in MFS-SuperEnsemble-BHM. Figure 1 depicts the Eastern Mediterranean and the locations of upper ocean profile observations (T(z) and S(z)) from which the presence of LIW can be deduced.

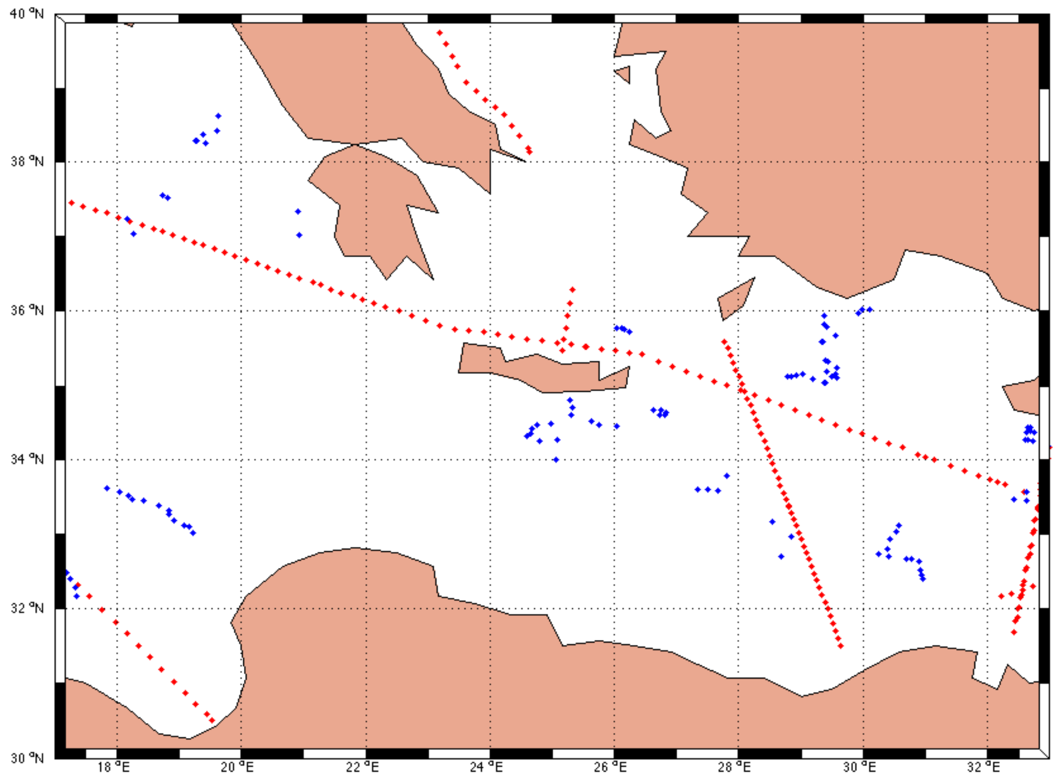

Figure 1. A portion of the Eastern Mediterranean containing the Rhodes Gyre (27E to 32E). The Rhodes Gyre region will be the locus of initial MFS-SuperEnsemble-BHM experiments to estimate average T, S indicative of LIW formation. Red markers denote XBT profiles from Volunteer Observing Ships, and blue markers denote profiles from ARGO. Observation locations span the period February-March 2005 (i.e. LIW formation season).

WORK COMPLETED AND RESULTS

Research program progress and plans were reviewed for ONR program managers by Milliff at the ONR SW Region Review in May 2008 at Scripps Institution of Oceanography.

The project's annual summer “Confab” was held in Boulder, in early August 2008. Refinements and sensitivity tests for MFS-Wind-BHM and MFS-Error-BHM were discussed, as were refinements in the experimental design for the initial multi-model formulations for MFS-SuperEnsemble-BHM. Following Milliff's visit and seminar at NRL SSC in November 2007, NRL scientists (Drs. Coelho and Richman) attended the Confab this year.

Work completed and results from the past year are reviewed by project in the following.

MFS-Wind-BHM

Bonazzi (2008) achieves the first complete implementation and impact study of MFS-Wind-BHM in an operational ocean forecast context. Bonazzi (2008) selected model A1E3 and sampled realizations from a posterior distribution after O(1000) iterations of the Gibbs Sampler, given fixed parameters for misfit terms in each velocity component (u,v) and the sea-level pressure (SLP).

Sensitivity tests in MFS-Wind-BHM have increased the iterations to O(10,000), and added full conditionals for the misfit terms to the Gibbs Sampler. In addition, hyperprior (i.e. coefficient initial values) specifications were set to so-called “analytic” values, and variances on the hyperpriors were specified to be large. The posterior mean parameter values for pressure-gradient coefficient terms are sensitive to these changes. Figure 2 shows the Gibbs Sampler iteration traces for a calculation wherein the parameter values change after about 18,000 iterations, from values close to those identified by Bonazzi (2008), to a different final state. The final state has been verified by repeat calculations where the Gibbs Sampler is iterated 100,000 times.

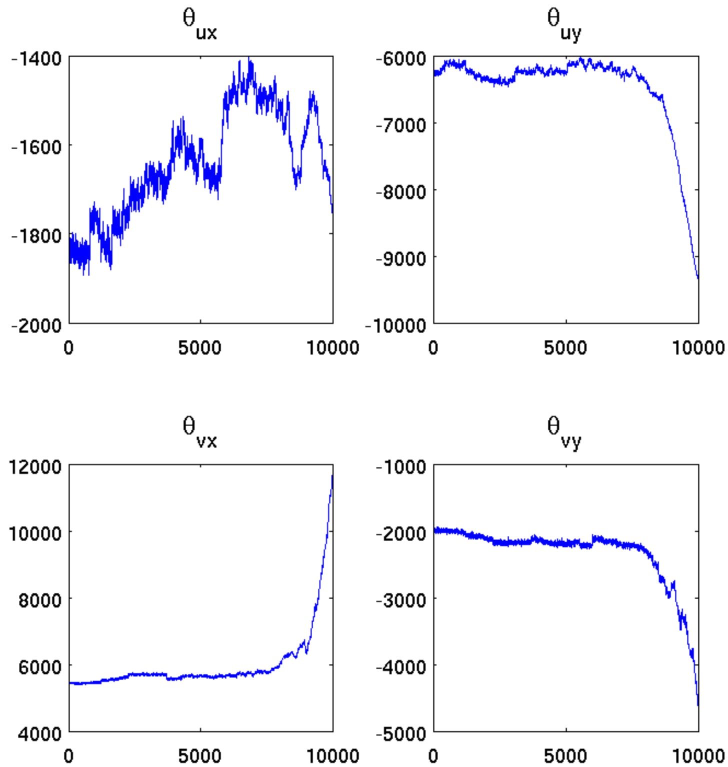

Figure 2. Gibbs Sampler iteration traces for the last 10,000 iterations of a 20,000 iteration calculation for the A1E3 version of MFS-Wind-BHM. The coefficient parameter values are changing (after about iteration 18,000) to values in a final state that differs from posterior mean values in Bonazzi (2008), and differs from so-called "analytic" values.

Simulated data experiments are in progress now to diagnose posterior distribution sensitivities to parameters of the MFS-Wind-BHM model hierarchy. Simulated data include purely geostrophic winds consistent with the circulation around an idealized low pressure system that propagates through the MFS-Wind-BHM domain. In this case, we expect the posterior distribution to return "analytic" amplitudes for the geostrophic parameters, and nearly 0 amplitudes for the ageostrophic parameters.

MFS-Error-BHM

The first set of MFS reforecast tests of the impacts of time-dependent background error covariance matrices from MFS-Error-BHM have been completed. Figure 3 depicts the negative impacts obtained thus far.

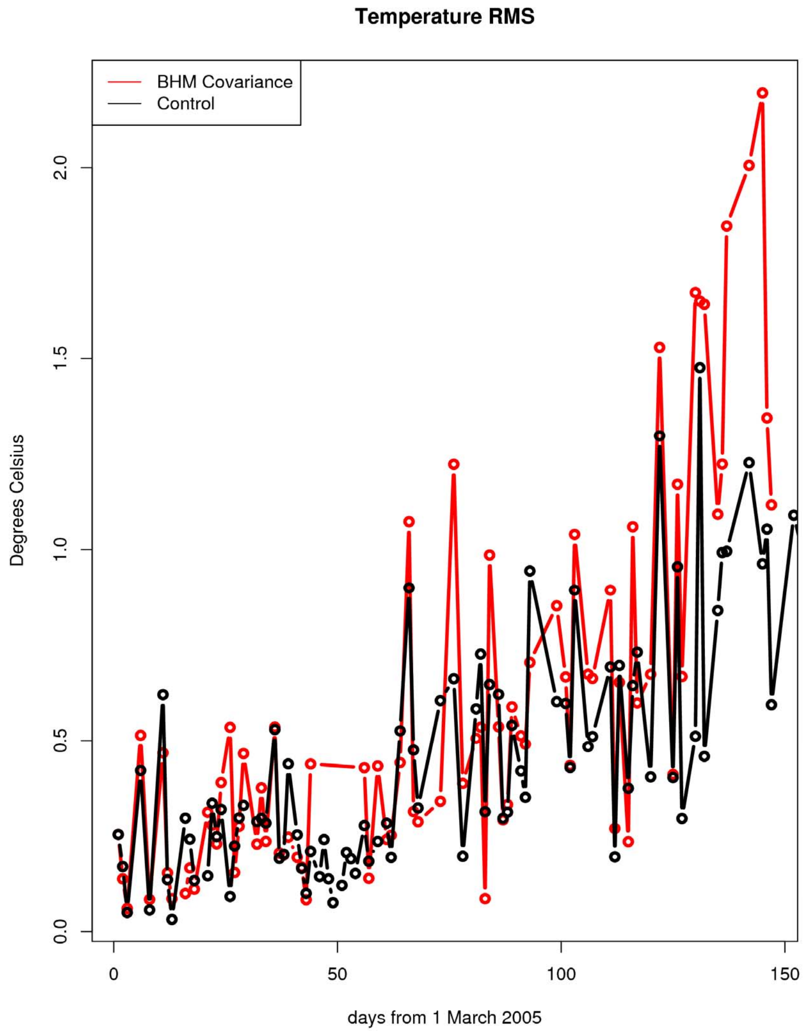

Figure 3. Root-mean-square differences with respect to ARGO T(z) in reforecast experiments comparing the existing MFS background error covariance (black line) with time-dependent background error covariance from MFS-Error-BHM (red). The reforecast experiments span a period of 150 days from 1 March 2005. The absence of red dots for a 5-day period centered on day 50 is due to a failure for the cost function to converge in the MFS 3DVAR during this time.

While discrepancies are small (< 0.5º) through day 100 (i.e. about June), the MFS-Error-BHM impacts are mostly negative. The discrepancies grow after day 100 such that error differences of several degrees are seen in July and August.

Initial negative impacts on this scale are not surprising given the shock to the operational forecast system that daily changes to the background error covariance might imply. Increasing the importance of anomaly inputs to the data stage distribution for MFS-Error-BHM (i.e. with respect to misfit inputs) is one way of smoothing the temporal variability of the posterior mean background error covariance estimate. Sensitivity tests of this kind are expensive (i.e. reforecast experiments must be run in the full MFS model), but they are proceeding at INGV nonetheless.

MFS-SuperEnsemble-BHM

The multi-model form of MFS-SuperEnsemble-BHM development is in initial stages of implementation, including the assembly of ocean simulations and analyses from: a) the MFS operational analyses (version sys2b at the time of the Confab); b) the MFS simulations done with NEMO; and c) the MedROMS implementation from Georgia Tech. Daily temperature and salinity fields will be summarized over a rectangular region of the Eastern Mediterranean centered on the Rhodes Gyre, from 0-400*m*, for February-March for the years 2005-2008. The data period has been shifted forward so as to occur after the introduction, in 2003, of ARGO data and the data assimilation system adjustments that occurred thereafter. To insure efficient technology transfer from the climate-scale application of Berliner and Kim (2008), we will define MFS-SuperEnsemble-BHM targets to be time series of scalars (Berliner and Kim, 2008 used hemispheric average temperature). The scalar target time series are defined as the spatially averaged T and S in a limited-area domain centered on the Rhodes Gyre, at a single layer (say 200*m*), or spanning a range of depths (i.e. 150-250*m*). These MFS-SuperEnsemble-BHM targets focus on properties relevant to the LIW during the formation and spreading periods each year.

Figure 4 depicts analysis and model salinity field snapshots in the Eastern Mediterranean at 250*m* from MFS-sys2b analyses (top row) and MedROMS simulations driven by 2 different wind datasets (ECMWF winds, middle row; and QuikSCAT winds, bottom row).

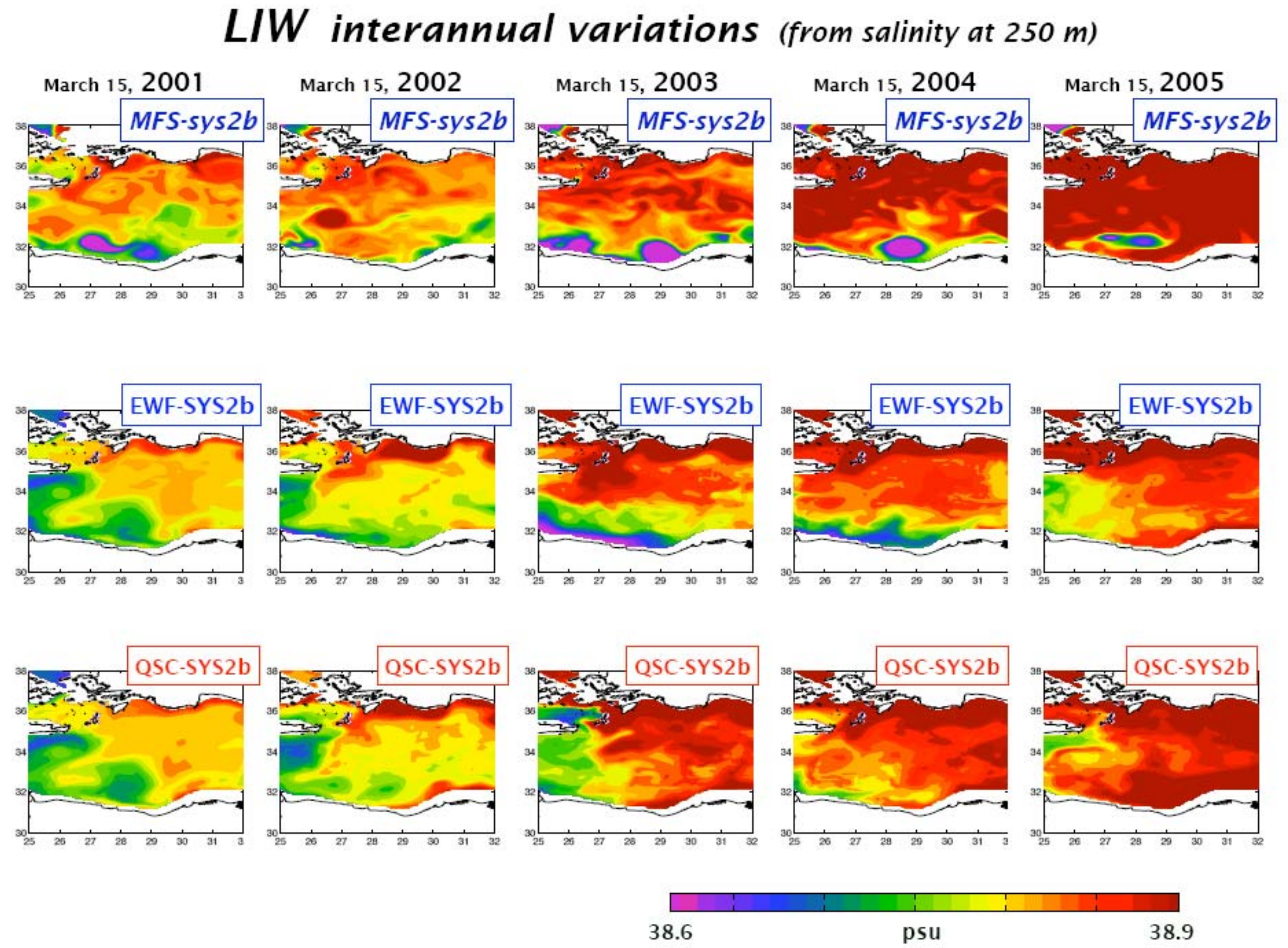

Figure 4. Salinity fields at 250m from MFS analyses (top) , MedROMS forced by ECMWF winds (middle), and MedROMS forced by QuikSCAT (bottom). The MedROMS simulations are started on 15 January. Snapshots for 15 March in each of 5 successive years are shown here to infer interannual variability in LIW.

The figure infers the interannual variability in LIW for the region, and demonstrates increasing salinity at the depth of the LIW over the 5 years shown. The impacts of different surface wind forcings are also evident, with QuikSCAT forcing leading to greater salinities at 250m and more eddy-scale variability. Note that ARGO data were introduced to the analyses in 2003.

IMPACTS AND APPLICATIONS

Milliff traveled to NRL SSC (Ocean Modeling Group) in November 2007 to give a seminar on Phase I research results to date. NRL scientists are interested in BHM applications to ocean forecasting. Drs. Emanuel Coelho and James Richman attended the Confab in 2008, and plans are proceeding to include NRL model inputs to MFS-SuperEnsemble-BHM in the near future.

Wikle and Milliff are invited speakers at a National Research Council workshop on "Uncertainty Management in Remote Sensing of Climate Data" in December 2008. They will coordinate their talks to review understandings gained in the research in MFS-Wind-BHM.

RELATED PROJECTS

NSF-C433P-RFM-CORA-1433:
"Collaborative Research: Estimating Ecosystem Model Uncertainties in Pan-Regional Syntheses and Climate Change Impacts on Coastal Domains of the North Pacific Ocean". Co-PIs include Wikle and Milliff; Advisory Council includes Berliner. Period of Performance September 2008- August 2011.

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